

Orientation of 1s electrons using tilted foils

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Abstract. The prospects for producing orientation of the 1s level in highly charged ions using tilted foils is discussed. We analyse the transfer of orientation from the initial orbital angular momentum of an ion emerging from a foil to the ground-state spin via a combination of the spin-orbit interaction and cascade decays. An enhancement of the orientation can be obtained using a multi-tilted-foil technique similar to that used to orient nuclei.

1. Introduction

Beams of oriented† ions have numerous applications in atomic physics experiments, including measurements of atomic structure and studies of collisions with atoms or electrons [1, 2]. Many different methods are employed for producing beams of oriented ions, such as direct optical pumping [3], scattering off of magnetic surfaces [4], transmission through magnetic layers [5, 6], charge exchange in spin-polarized targets [7–14], transmission through tilted foils [15–20], scattering from inclined surfaces [21–24] and use of multi-tilted foils or surfaces [21, 25–31]. Of these the least expensive and most universally applicable are the methods involving tilted foils and surfaces [32]. In this paper we analyse the potential for using tilted foils to produce beams of ions with oriented 1s electrons. Such beams are useful in measurements of hyperfine structure [33, 34], and after excitation of the electron to 2s could be used in tests of weak interaction theory by measurements of parity nonconservation [35, 36], and measurements of fundamental atomic structure properties via asymmetry measurements [37, 38].

At first glance, the tilted-foil method seems unsuitable for the production of oriented s states. In the beam-tilted-foil interaction, it is the orbital angular momentum that is oriented. Although angular momentum is transferred to the spin degrees of freedom via the spin-orbit interaction [39, 40], an ion formed directly in an s state cannot be oriented in this way. We consider in this paper two ways that can produce oriented 1s states, however. One is the capture of an electron into a H-like state of non-zero orbital angular momentum followed by a cascade to the ground state. The other is by transfer of angular momentum from outer electrons to a 1s spin via the spin-orbit interaction. The first possibility will be analysed in sections 2 and 3 where the transfer of orientation from an initial H-like excited state through its subsequent cascade decay to the ground state will be analysed. The other mechanism will be explored in sections 4 and 5, where we consider a multi-tilted-foil scheme for orienting 1s electrons. In these discussions we will not be concerned with the mechanism for the production of the initial orientation by the tilted foil or surface. This

† By orientation we mean that one of the $K = 1$ state multipoles (see equation (1)) is non-zero.

has been discussed by a number of authors [41–51]. We will simply assume that the ions emerging from a tilted foil have oriented orbital angular momentum.

The multi-tilted-foil technique has been used to enhance the orientation of nuclear spins produced by a tilted-foil polarizer [21, 30, 31]. The tilted foil produces oriented orbital angular momentum and the hyperfine interaction transfers orientation to the nucleus. In the multi-foil method, the ions pass through many tilted foils. It is assumed that the electronic state is destroyed in the interior and then recreated at the exit of each foil, while the nuclear spin exits the foil in the same state it entered. The transfer of angular momentum to the nucleus via the hyperfine interaction accumulates over many foils.

In general, the multi-foil method is not useful for enhancing electronic polarization since the electronic state exiting a foil has no ‘memory’ of the state entering the foil†. But we show here that an atomic analogue of the multi-foil method could be useful for orienting K electrons by successive destruction and regeneration of *outer* electrons. In this case, the spin–orbit interaction replaces the hyperfine interaction as the orientation transfer mechanism. A key point is that the foils must be thin enough that the 1s electrons have a small probability of being stripped or excited in a foil. This condition is satisfied in the limit of high-velocity ions interacting with thin foils.

2. Orientation of H-like ions

We begin by analysing the coupling of angular momentum downstream of a tilted foil for the simple case of a one-electron ion. In this analysis, we will use the notation of Blum [52] in which the state multipoles for a density matrix ρ with elements $\langle JM|\rho|J'M'\rangle$ are defined by:

$$\langle T(J'J)_{KQ}^\dagger \rangle = \sum_{M'M} (-1)^{J'-M'} (2K+1)^{1/2} \begin{pmatrix} J' & J & K \\ M' & -M & -Q \end{pmatrix} \langle JM|\rho|J'M'\rangle. \quad (1)$$

The density matrix can be expanded in terms of these giving:

$$\rho = \sum_{J'JKQ} \langle T(J'J)_{KQ}^\dagger \rangle T(J'J)_{KQ} \quad (2)$$

where the $T(J'J)_{KQ}$ are tensor operators defined by:

$$T(J'J)_{KQ} = \sum_{M'M} (-1)^{J-M} (J'M', J-M|KQ)|J'M'\rangle \langle JM|. \quad (3)$$

Consider a one-electron ion which emerges from a tilted foil in a state with orbital angular momentum L . We assume that at $t = 0$ the spin and orbital angular momenta are uncoupled and the spin is not oriented [53]. The density matrix at $t = 0$ is:

$$\rho(0) = \frac{1}{2S_1 + 1} \sum_{kq} \langle T(L)_{kq}^\dagger \rangle [T(L)_{kq} \times \mathbf{1}_{S_1}]. \quad (4)$$

Here, S_1 is the spin of the captured electron and $\mathbf{1}_{S_1}$ is the unit operator in spin space. We take the nuclear spin to be zero. The tilted-foil interaction will generally produce states with oriented orbital angular momentum which means that the state multipoles $\langle T(L)_{kq}^\dagger \rangle$ with $k = 1$ are non-zero. Also, we take the quantization axis to be along the direction of the orientation so that only the $q = 0$ component $\langle T(L)_{10}^\dagger \rangle$ is non-zero [17, 18].

† Except that nuclear orientation would couple back to the electronic state via the hyperfine interaction. This will not be considered here because we will take the nuclear spin to be zero.

After evolving for a time t , the density matrix becomes:

$$\rho(t) = \frac{1}{2S_1 + 1} \sum_{k,q,k',q'} \langle T(L)_{kq}^\dagger \rangle U(t) [T(L)_{kq} \times \mathbf{1}_{S_1}] U(t)^\dagger \quad (5)$$

where $U(t)$ is the time-development operator. Defining time-dependent state multipoles in the basis of the total angular momentum J :

$$\langle T(JJ', t)_{KQ}^\dagger \rangle = \text{tr} \rho(t) T(JJ')_{KQ} \quad (6)$$

and using equation (5) we find:

$$\langle T(JJ', t)_{KQ}^\dagger \rangle = \frac{1}{2S_1 + 1} \sum_{kq} \langle T(L)_{kq} \rangle^\dagger \text{tr} \{ U(t) [T(L)_{kq} \times \mathbf{1}_{S_1}] U(t)^\dagger T(JJ')_{KQ} \}. \quad (7)$$

The matrix representation of $U(t)$ is diagonal in the J basis:

$$\langle (LS')J'M' | U(t) | (LS)JM \rangle = \exp(-iE_J t/\hbar) \delta_{JJ'} \delta_{MM'} \delta_{SS'}. \quad (8)$$

Using equation (8) in (7) and taking the trace we find:

$$\begin{aligned} \langle T(JJ', t)_{KQ}^\dagger \rangle &= \frac{1}{2S_1 + 1} \sum_{\substack{kq \\ JM \\ J'M'}} \langle T(L)_{kq} \rangle^\dagger \exp \left[\frac{i(E_J - E_{J'})t}{\hbar} \right] \\ &\times \langle (LS_1)J' | T(L)_{kq} \times \mathbf{1}_{S_1} | (LS_1)J \rangle \langle (LS_1)J | T(JJ')_{KQ}^\dagger | (LS_1)J' \rangle. \end{aligned} \quad (9)$$

The matrix elements can be evaluated using standard formulae of angular momentum theory [52, 54] with the result:

$$\begin{aligned} \langle T(JJ', t)_{kq}^\dagger \rangle &= \frac{1}{2S_1 + 1} \langle T(L)_{kq} \rangle^\dagger \sum_{JJ'} \exp \left[\frac{i(E_J - E_{J'})t}{\hbar} \right] (-1)^{L+S_1+J+k} \\ &\times [(2J' + 1)(2J + 1)]^{1/2} \begin{Bmatrix} L & J' & S_1 \\ J & L & k \end{Bmatrix}. \end{aligned} \quad (10)$$

The time dependence is contained in the exponential terms which give rise to oscillations at the frequencies of the fine-structure splittings. These terms will typically average to zero over time scales of interest here and we need only consider the time-averaged state multipoles:

$$\langle T(J)_{kq} \rangle = \frac{2J + 1}{2S_1 + 1} (-1)^{L+S_1+J+k} \begin{Bmatrix} L & J & S_1 \\ J & L & k \end{Bmatrix} \langle T(L)_{kq} \rangle^\dagger. \quad (11)$$

For a given initial orientation of the orbital angular momentum at the foil exit, equation (11) gives the desired relation for the time-averaged orientation of the total angular momentum downstream of a tilted foil. For direct capture into an s state, only $\langle T(L)_{00}^\dagger \rangle$ is non-zero so there is no orientation. However, if the s state is populated via cascades originating from states of non-zero orbital angular momentum then it can be oriented. In the next section we will analyse this process.

3. Cascades

The transfer of alignment and orientation in cascade transitions has been treated by a number of authors [55–57]. We will use the relations derived by Lin and Macek [57]. The electron is initially in a state of orbital angular momentum L_N which couples to form a multiplet of states of total orbital angular momenta J_N . For each fine-structure level J_N , the cascade

proceeds through all possible intermediate transitions $J_{i+1} \rightarrow J_i$, to a member of the final state multiplet J_1 with orbital angular momentum L_1 . The transformation of state multipoles is given by equation (7) of Lin and Macek's paper [57]:

$$\langle T(J_1)_{kq}^\dagger \rangle = \prod_i C_i \sum_{J_N} D(k, J_1 J_N) \langle T(J_N)_{kq} \rangle \quad (12)$$

where:

$$D(k, J_1 J_N) = \sum_{J_2, J_3, \dots, J_{N-1}} B(k, J_1 J_2) B(k, J_2 J_3) \cdots B(k, J_{N-1} J_N), \quad (13)$$

$$B(k, J_i J_{i+1}) = (2J_{i+1} + 1)(2J_i + 1)(-1)^{J_{i+1} + J_i + k + 1} \\ \times \left\{ \begin{matrix} L_{i+1} & J_{i+1} & S \\ J_i & L_i & 1 \end{matrix} \right\}^2 \left\{ \begin{matrix} J_{i+1} & J_i & 1 \\ J_i & J_{i+1} & k \end{matrix} \right\}. \quad (14)$$

The C_i are normalization constants which contain information on branching ratios, etc. They will not be considered further here since we shall always work with ratios of the state multipoles and these constants will cancel.

To estimate the transfer of angular momentum following excitation in a tilted foil, we assume the ion is formed in a state with orbital angular momentum L_N and it decays to the final state via the simplest cascade chain in which the orbital angular momentum decreases by one unit in each step. With this simplification, the results will be independent of the principal quantum number n of the initial state. We take the initial orbital orientation P_L to be the same for each L_N , and for simplicity, we take the state multipoles $\langle T(L)_{kq}^\dagger \rangle$ with $k > 1$ to be zero, although this imposes conditions on the maximum orientation possible [24]. The relation between P_L and the initial orbital state multipole is:

$$P_L \equiv \frac{\langle L_z \rangle}{L_N} = \langle T(L_N)_{10} \rangle \left[\frac{(L_N + 1)(2L_N + 1)}{3L_N} \right]^{1/2} \quad (15)$$

where L_z is the operator for the z component of orbital angular momentum.

To calculate the final state multipoles, we use equations (11) and (15) to determine the initial state multipoles in the coupled basis $\langle T(J_N)_{k0}^\dagger \rangle$ and then apply equation (12). For s states of H-like ions there is only one component of the final-state multiplet, i.e. $J_1 = \frac{1}{2}$. The spin orientation P_S in this case is given by the ratio:

$$P_S \equiv \frac{\langle S_z \rangle}{S_1} = \frac{\langle T(J_1)_{10}^\dagger \rangle}{\langle T(J_1)_{00}^\dagger \rangle}. \quad (16)$$

Table 1. Orientation transfer via cascades for H-like ions. Initial orbital angular momentum orientation $P_L = 0.12$ and zero alignment assumed.

Initial L	Orientation of $1s^2S_{1/2}$ state
1	0.0533
2	0.0598
3	0.0617
4	0.0625
5	0.0630
6	0.0632
7	0.0634
8	0.0635

The results for P_S are given in table 1 for L_N from 1 to 8, where we have assumed $P_L = 0.12$. The orientation increases with increasing L_N , asymptotically approaching a value just above 50% of P_L . The maximum P_S for capture into a p state is 44% of P_L . These results indicate that significant orientation can be transferred to a 1s electron. It also indicates that there is an advantage to capture into states with higher orbital angular momentum. In an actual experiment, the polarization would be lower because some of the ions will be captured directly into s states and these will not be oriented. In section 5.2 we present the results of a Monte Carlo calculation which takes this into account.

4. Formation of He-like ions

For a He-like ion emerging from a foil, the time-dependent density matrix is given by:

$$\rho(t) = \frac{1}{2S_1 + 1} \sum_{k,q,k',q'} \langle T(L)_{kq}^\dagger \rangle \langle T(S_2)_{k'q'}^\dagger \rangle U(t) [T(L)_{kq} \times (\mathbf{1}_{S_1} \times T(S_2)_{k'q'})] U(t)^\dagger. \quad (17)$$

One of the electrons is assumed to be in the ground state and its spin S_2 may be oriented from interactions in a previous foil. The other electron spin (represented by the identity operator) is initially unpolarized. For simplicity we assume LS coupling even though this is strictly only applicable for low L and low nuclear charge Z . The time-dependent state multipoles in the coupled representation are obtained using equations (6), (8), (17) and standard results from angular momentum theory [52, 54] with the result:

$$\begin{aligned} \langle T(JJ', t)_{KQ}^\dagger \rangle &= \frac{1}{2S_1 + 1} \sum_{kqk'q'} \langle T(L)_{kq}^\dagger \rangle \langle T(S_2)_{k'q'}^\dagger \rangle \exp \left[\frac{i(E_{J(S)} - E_{J'(S')})t}{\hbar} \right] \\ &\times (-1)^{S_1+S_2+S'+K'} [(2J+1)(2J'+1)(2k+1)(2k'+1)(2S'+1)(2S+1)]^{1/2} \\ &\times \left\{ \begin{matrix} S_2 & S' & S_1 \\ S & S_2 & k' \end{matrix} \right\} \left\{ \begin{matrix} L & L & k \\ S' & S & k' \\ J' & J & K \end{matrix} \right\} \langle kk'KQ | kqk'q' \rangle. \end{aligned} \quad (18)$$

The time dependence is exhibited in the exponential factors in this expression. The energy levels for a given L are labelled by both the spin S (singlet or triplet) and the total angular momentum J . Oscillations occur at frequencies corresponding to the various energy splittings. We are interested in the limit of long times relative to the oscillation periods so the time-dependent terms average to zero. In this case the (time-independent) state multipoles are given by:

$$\begin{aligned} \langle T(J)_{KQ}^\dagger \rangle &= \frac{1}{2S_1 + 1} \sum_{kqk'q'} \langle T(L)_{kq}^\dagger \rangle \langle T(S_2)_{k'q'}^\dagger \rangle \\ &\times (-1)^{S_1+S_2+S+K'} (2J+1)(2S+1)[(2k+1)(2k'+1)]^{1/2} \\ &\times \left\{ \begin{matrix} S_2 & S & S_1 \\ S & S_2 & k' \end{matrix} \right\} \left\{ \begin{matrix} L & L & k \\ S & S & k' \\ J & J & K \end{matrix} \right\} \langle kk'KQ | kqk'q' \rangle. \end{aligned} \quad (19)$$

This is similar to a formula derived in connection with the capture of spin-polarized electrons from magnetic materials [58].

For ions that emerge from the foil in excited states, the transfer of orientation and alignment via cascades can be taken into account using equation (12). As before, we label the state multipoles of the capture-state multiplet by the quantum number J_N and propagate to the final-state multiplet J_1 . For metastable final states, the K-shell is not filled and S_2

may be oriented. The state multipoles for S_2 are expressed in terms of the state multipoles of J_1 by:

$$\langle T(S_2)_{k'q'}^\dagger \rangle = \sum_{\substack{kq \\ J_1 S}} \langle T(J_1)_{kq}^\dagger \rangle \text{tr}\{[\mathbf{1}_{L_1} \times (\mathbf{1}_{S_1} \times T(S_2)_{k'q'})]T(J_1)_{kq}\} \quad (20)$$

which gives

$$\begin{aligned} \langle T(S_2)_{kq}^\dagger \rangle &= \sum_{J_1 S} \langle T(J_1)_{kq}^\dagger \rangle (-1)^{J_1+L_1+2S+1} (2J_1+1)(2S+1) \\ &\times \left\{ \begin{matrix} S & J_1 & L_1 \\ J_1 & S & k \end{matrix} \right\} \left\{ \begin{matrix} S_2 & S & S_1 \\ S & S_2 & k \end{matrix} \right\}. \end{aligned} \quad (21)$$

This is also the state multipole that would be formed by suddenly stripping off the outer electron of an excited He-like ion, without disturbing the 1s state spin.

5. Multi-foil array

We have used the relations presented in sections 2–4 as the basis for two different simple models of the electronic orientation produced by an array of tilted foils.

5.1. Nuclear analogue

First we consider an analogue of the models used to analyse nuclear polarization produced by multi-tilted foils and surfaces [21, 26, 30, 31]. We assume that within a foil, the electronic states of the outer electrons ($n \geq 2$) are destroyed, but the ions exit each foil in the same state of excitation characterized by a specific angular momentum L_N and an orientation P_L . For ions that enter a foil with one K electron (e.g. He-like metastable states), we assume the 1s spin emerges from the foil in the same state in which it entered.

In the model, it is assumed that only the multipoles $\langle T(L_N)_{kq}^\dagger \rangle$ with $k = 0$ or 1 are non-zero. Also, for $S_2 = \frac{1}{2}$, only the state multipoles $\langle T(S_2)_{k'q'}^\dagger \rangle$ with $k' = 1, 0$ and $q' = 0$ are non-zero. Combining equations (12), (19), and (21) we derive the following result for the ratio of state multipoles $(\langle T(S_2)_{K0}^\dagger \rangle / \langle T(S_2)_{00}^\dagger \rangle)_{i+1}$ for ions entering foil $i+1$ in terms of the ratio $(\langle T(S_2)_{k'0}^\dagger \rangle / \langle T(S_2)_{00}^\dagger \rangle)_i$ for ions entering the previous foil i :

$$\left(\frac{\langle T(S_2)_{K0}^\dagger \rangle}{\langle T(S_2)_{00}^\dagger \rangle} \right)_{i+1} = \frac{\sum_{k'K} G_{k'K} (\langle T(S_2)_{k'0}^\dagger \rangle / \langle T(S_2)_{00}^\dagger \rangle)_i}{\sum_{k'} G_{k'0} (\langle T(S_2)_{k'0}^\dagger \rangle / \langle T(S_2)_{00}^\dagger \rangle)_i} \quad (22)$$

where the $G_{k'K}$ are given by:

$$\begin{aligned} G_{k'K} &= \sum_{\substack{kJ_N \\ J_1 S}} (-1)^{J_1+3S+k'} (2J_1+1)(2J_N+1)(2S+1)^2 [(2k+1)(2k'+1)]^{1/2} \\ &\times \left\{ \begin{matrix} S & J_1 & L_1 \\ J_1 & S & K \end{matrix} \right\} \left\{ \begin{matrix} S_2 & S & S_1 \\ S & S_2 & K \end{matrix} \right\} \left\{ \begin{matrix} S_2 & S & S_1 \\ S & S_2 & k' \end{matrix} \right\} \left\{ \begin{matrix} L_N & L_N & k \\ S & S & k' \\ J_N & J_N & K \end{matrix} \right\} \\ &\times \langle kk'K0 | k0k'0 \rangle D(K, J_1 J_N) \langle T(L_N)_{k0}^\dagger \rangle. \end{aligned} \quad (23)$$

The factor $D(K, J_1 J_N)$ accounts for cascades from the initial state L_N to lower states in the region between the foils (see equation (13)).

Equation (22) gives P_s for the ground-state spin after passage of an ion through the multi-foil array. The ion starts out bare and emerges from the first foil in an H-like state with angular momentum L_N , and orientation $P_L = 0.12$. This state cascades to the ground

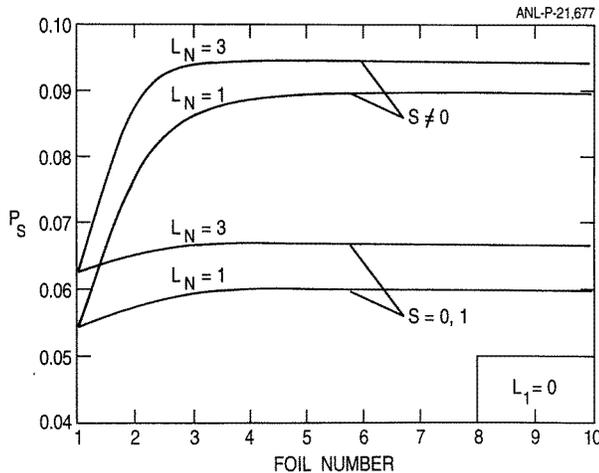


Figure 1. Orientation P_S versus foil number for an unpaired ground-state spin. L_N and L_1 are the orbital angular momenta for the initial and final states. Here $L_1 = 0$. The calculations leading to the upper curves did not include singlet final states, whereas for the lower curves both singlet and triplet final states were included.

state acquiring an orientation (see table 1). In all subsequent foils the ion emerges in a He-like excited state, also with orbital angular momentum L_N and orientation $P_L = 0.12$. The He-like states cascade to the ground state if they are singlets ($S = 0$) or to $n = 2$ if they are triplets ($S = 1$). It is assumed that the $n = 2$ triplet states do not decay between foils. The final orbital angular momentum is either an s state ($L_1 = 0$) or a p state ($L_1 = 1$) and these cases are treated separately.

The results of the model are given by the curves labelled ' $S \neq 0$ ' in figures 1 and 2, which are graphs of P_S as a function of foil number for various values of L_N . Figure 1 shows the results for s states and figure 2 shows the results for the p states. To exclude ions with filled K-shells the singlets ($S = 0$) are not included in the sum over S in either of the factors $G_{k'K}$ or $G_{k'0}$ of equation (22). We assume here that ions with a filled K-shell can be separated by, for example, preferential stripping of outer electrons followed by magnetic selection of the one-electron species.

An important assumption in this model is that the He-like triplet states have long lifetimes compared with the transit time of the ions between the foils. If these states decay to $1s^2 \ ^1S_0$, the 1s orientation is destroyed. To explore the limits of validity of the model we present in figure 3 the lifetimes of the $n = 2$ He-like states [59, 60] as a function of nuclear charge Z . These can be compared with the minimum transit times in multi-foil experiments which are about 10 ps [61]. At low Z , all of the triplet states have lifetimes long enough to survive the transit. For $Z > 15$, however, the $1s2p \ ^3P_1$ state decays (mostly to the ground state via mixing with $1s2p \ ^1P_1$ state) with a lifetime too short to survive to an adjacent foil. This means that ions in the $1s2p \ ^3P_1$ level of higher- Z ions quickly decay to the ground state and enter the next foil with filled K-shells so the model is not valid in this regime. We can extend the model to higher Z by excluding the $1s2p \ ^3P_1$ state in the sums over J_1 in equation (23). The curves labelled ' $J_1 \neq 1$ ' in figure 2 are the results obtained from this extended model. It is interesting that the orientation is significantly enhanced by the exclusion of the $J_1 = 1$ states, the maximum orientation being larger than that of the initial orbital angular momentum. The cost of this enhancement is that there is a smaller

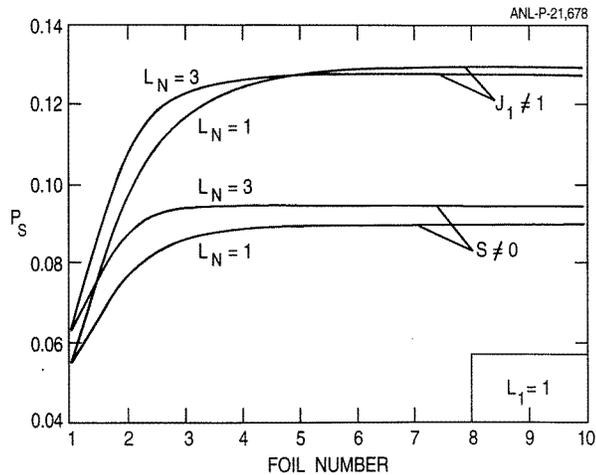


Figure 2. Same as figure 1, except that $L_1 = 1$. The calculations leading to the upper curves did not include final states with total angular momentum $J_1 = 1$ and the calculations for the lower curves did not include the singlet final states.

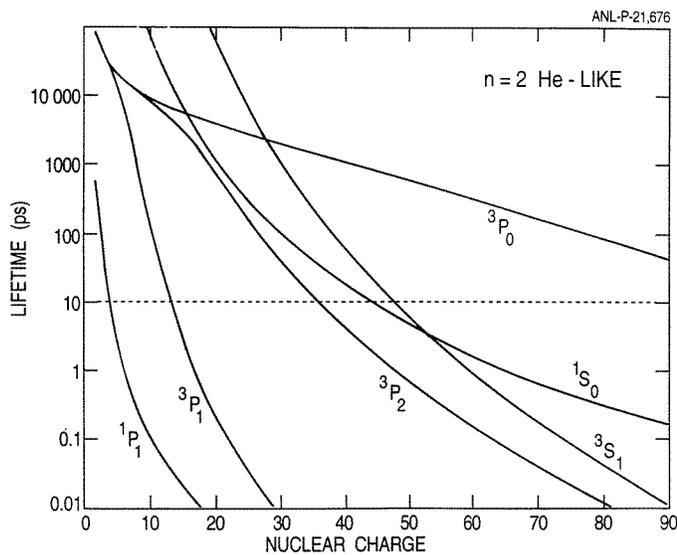


Figure 3. Lifetimes of the $n = 2$ levels of He-like ions versus nuclear charge.

fraction of the beam with one K electron. The extended model is useful up to about $Z = 36$, beyond which the $1s2p\ ^3P_2$ level decays (mostly to the ground state via an M2 transition) with a lifetime too short to survive the transit between foils. It should be pointed out though that the assumption of LS coupling is not valid in this region of Z , so these results are only qualitative.

Another conclusion from figure 3 is that the neglect of the singlet states is only partially valid since the lifetime of the $1s2s\ ^1S_0$ state is long enough that it would survive the transit to an adjacent foil for $Z < 45$. This state would contribute to the fraction of the beam with one K electron and since it is not oriented, including it would reduce the orientation

predicted by the model. This is illustrated by the curves labelled ' $S = 0, 1$ ' in figure 1 which were obtained by retaining both the singlet and triplet terms in equation (23). As expected, these show a smaller maximum orientation. The justification for neglecting the $1s2s^1S_0$ state in the simple model is that this state is not likely to be populated via cascades since higher lying p states decay mostly to the $1s^2^1S_0$ ground state. In the next section, we discuss a simple Monte Carlo model which does include the depolarizing effect of the $1s2s^1S_0$ level by allowing capture or excitation directly to this state.

5.2. Simple Monte Carlo simulation

In order to provide a more realistic estimate of the 1s orientation to be expected from a multi-tilted-foil array, we developed a simple Monte Carlo simulation based on calculated cross sections for capture [62], stripping and ionization [63]. The simulation not only provides estimates of the orientation as a function of foil number, but also of the fraction of ions that emerge from the tilted-foil array with one K electron. Each iteration of the simulation takes an ion through a fixed number of tilted foils. At each foil, electrons are captured, excited, or stripped according to probabilities determined from the cross sections. If an ion emerges from a foil in a state of non-zero orbital angular momentum L_N , it is assumed to have an orientation P_L independent of the capture state. The development of the density matrix between the foils follows closely the treatment described in section 5.1.

The distance between adjacent foils is not a parameter in the simulation, but it is assumed that the time-of-flight of the ions between the foils is long compared to the angular momentum coupling times in the initial state and short compared to the lifetimes of the metastable He-like $n = 2$ states. The first assumption allows us to use the time-independent solutions given by equations (11) and (19), and is generally valid for states populated with appreciable probability. The importance of the assumption concerning the lifetimes of $n = 2$ levels was discussed in section 5.1.

Results of the simple Monte Carlo simulation for bare, 500 MeV argon ions incident on an array of thin ($\sim 3 \mu\text{g cm}^{-2}$) gold foils are presented in figure 4. The orientation P_S

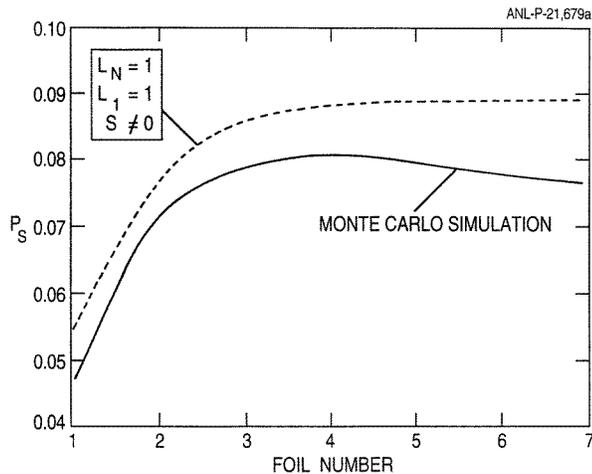


Figure 4. Results of the simple Monte Carlo simulation, giving the orientation P_S as a function of the foil number. The $L_N = 1, L_1 = 1, S \neq 0$ case from figure 2 is also shown for comparison (broken curve).

is plotted as a function of foil number for an initial orientation $P_L = 0.12$. The maximum orientation is reached after only a few foils and drops slowly as the foil number increases. For comparison we also repeat the curve from figure 2 giving the result of the simple model of section 5.1 with parameters $L_N = 1$, $L_1 = 1$ and $S \neq 0$. As expected, the simulation gives a smaller maximum orientation but this is still 67% of P_L . Perhaps more importantly, the simulation shows a significant increase in orientation with use of more than one foil which suggests that the multi-foil technique could be useful in atomic physics experiments.

6. Conclusion

In this paper it is shown that under reasonable assumptions, significant orientation may be transferred to a K electron following tilted-foil excitation. This orientation may be enhanced using an analogue of the multi-tilted-foil technique used in nuclear physics. The results are also directly applicable to the problem of tilted surfaces and multi-tilted surfaces.

The models used in our analysis have left out many aspects of the highly complex beam-foil interaction and many simplifying assumptions have been made such as using LS coupling and including only one type of cascade decay chain. Also, the value chosen for the initial orientation P_L is arbitrary. These limitations are not expected to change the basic conclusions of this analysis. The final test of these ideas, however, requires experiments. In this respect, the models can be used as a guide in the choice of experimental parameters.

Although the emphasis in this paper has been on the production of ground-state spin, the general method could also be used for obtaining an oriented beam of H-like ions in the metastable $2^2S_{1/2}$ state. Assuming that the excitation mechanism is spin independent [53], orientation would be preserved in the excitation $1s \rightarrow 2s$ of an H-like ion. Production of an oriented $2s$ metastable beam would simply require an additional foil selected to optimize the excitation process. Such a beam would allow many fundamental atomic physics measurements with highly charged ions.

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